Normal and Diseased Vascular Pattern of Myocardium of Human Heart

I. Normal Pattern in the Left Ventricular Free Wall

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During the past 40 years investigations into the blood supply of the ventricles of the human heart have concentrated mainly on the problem of atheroma of the main portions of the coronary arteries and on arterial anastomoses. Little attention has been paid to the finer details of the normal and diseased patterns of arteries, arterioles, and capillaries within the myocardium.

Consequently, a study was carried out to establish the variations that exist within the normal pattern and then the changes that occur in hearts from patients with long-standing heart disease and, in particular, myocardial scarring or infarcts.

In order to do this a technique was devised which made possible the uniform injection of the smallest vessels of the heart, including capillaries, with radiopaque media, and a method of taking microradiographs was used which allowed considerably greater magnification of x-rays of these small vessels than had hitherto been possible.

This present paper describes the normal arterial pattern seen in the left ventricle of the human heart.

MATERIAL AND METHOD

Examinations were made of 52 hearts obtained at necropsy from patients who had died at the Veterans Administration Hospital, the Passavant Hospital, and the Children's Memorial Hospital in Chicago, in the United States of America†. The hearts were obtained at ran-

dom, irrespective of whether the patients were known to have died from heart disease or not. The patients fell into two general age categories: infants and children aged 2 weeks to 5 years and adults aged 37–80 years. Of the patients, 43 were Caucasian and 9 were Negroid. All were male, except for two of the children.

Of these hearts, 21, consisting of 4 from children and 17 from adults, were considered "normal", and 31 had either localized or diffuse lesions of either the right or left ventricles.

A radiopaque medium (Chromopaque, Damancy & Co.), with 4 per cent gelatin added, was injected into the coronary arteries at a pressure equivalent to the patient's systolic blood pressure, and by varying the viscosity of the medium it was possible to confine it to either small arteries, or to arterioles, or to achieve filling of capillaries (see Farrer-Brown, 1968). Cannulae of polyethylene tubing (Clay Adams) were ligated 2–3 mm. within the coronary arteries. The injection was carried out at 37° C. and the pressure was maintained for 15 or 30 minutes, respectively, in hearts from infants or adults, and for a varying time when filling of capillaries was desired without extensive flow into the venous system. After fixation the heart was sectioned on a bacon slicer from apex to base into uniform 5 mm. thick slices.

To show the general pattern of the large vascular supply of the myocardium these slices were x-rayed onto Superay Ansco x-ray film, using a G.E.C. x-ray unit, from which the filters had been removed, with exposures of 30 kV and 100 mA for two seconds, with a tube distance of 100 cm.

In order to demonstrate the finest vessels, selected slices were x-rayed by the contact method onto 4 × 5 in. Kodak high resolution plates, using a water-cooled, low voltage Machlett x-ray tube, with a beryllium window and copper target; 25 kV and 10 mA exposures were used for 15–30 minutes according to the thickness of the slice. The tube distance was 45 cm. When necessary the myocardial slices were recut on the bacon slicer into slices as thin as 1 mm. or into sections varying from 6–300 μ on a cryostat. Using these high resolution plates,
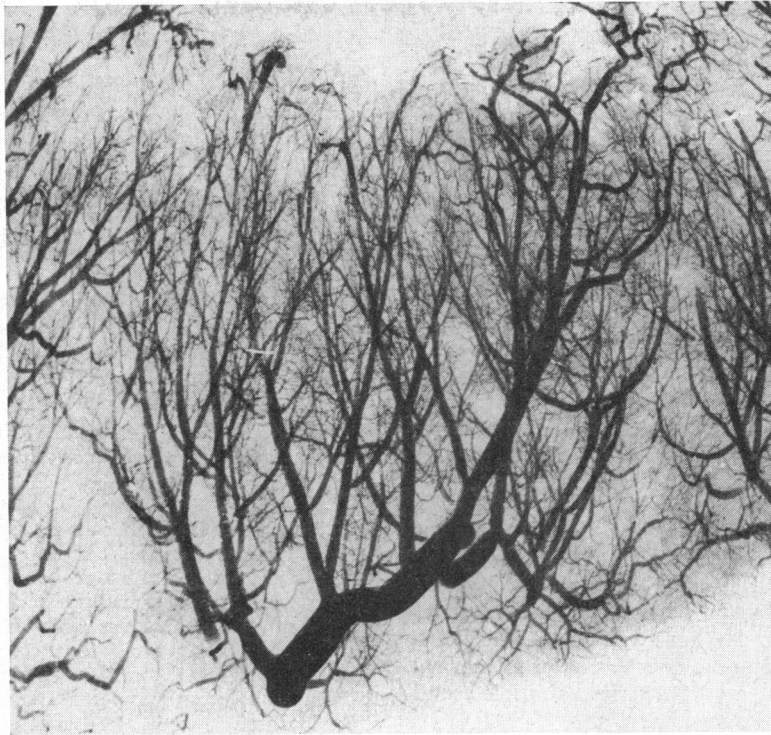
Fig. 1.—The "branching" type of artery supplying the left ventricular wall. (× 6·5.)

magnification of the microradiographs of capillaries up to 480 times was possible.

Portions of myocardium from the ventricles of all hearts were processed for histology.

RESULTS

The distribution of the main portions of the coronary arteries on the epicardial surface in 51 of the 52 hearts was similar to the earlier descriptions of Gross (1921), Spalteholz (1924), and Campbell (1929). One heart was an example of dextrocardia associated with a *situs inversus* in which the vascular supply was a complete mirror image of normal. The variation in "dominance" of the left and right coronary arteries in the supply of the posterior wall of the left ventricle did not appear to influence the pattern of the small arteries within the ventricular myocardium.

Microvasculature of Left Ventricular Free Wall. Branches from the main coronary arteries on the epicardial surface came off at right angles and coursed directly through the myocardial wall towards the endocardium. Initially these branches had an approximate diameter of 400–1500 μ, but most soon divided in a cascading tree-like pattern and gave off many small branches with gradually diminishing calibre (Fig. 1). These branching systems were regularly spaced around the left ventricle. A main stem was present every 5 mm. and an average of about 10 branching systems could be seen in the 5 mm. myocardial slices. Towards the apex, the circumference of the myocardial slice was smaller and there were fewer branching stems. At the apex, the obliquity of the muscle fibres and consequent change in direction in which the vessels were cut obscured this pattern.

The terminal branches of these arteries supplied the subendocardial zone of the ventricular wall (Fig. 2 and 3). This term is used to describe the innermost 2–3 mm. of the myocardium, but does not include the trabeculae carneae.

In addition to these "branching type" arteries there were a small number of "straight type" arteries that did not subdivide in this fashion, but instead gave off only a few twigs and maintained their calibre as they passed through the myocardium. The largest of these vessels, up to 500 μ in diameter, supplied the anterior and posterior papillary muscles while other slightly smaller vessels supplied the trabeculae carneae (Fig. 4). Sometimes these vessels appeared to vary in size along their course and to enlarge terminally. The anastomotic network of vessels in the subendocardial zone was mainly
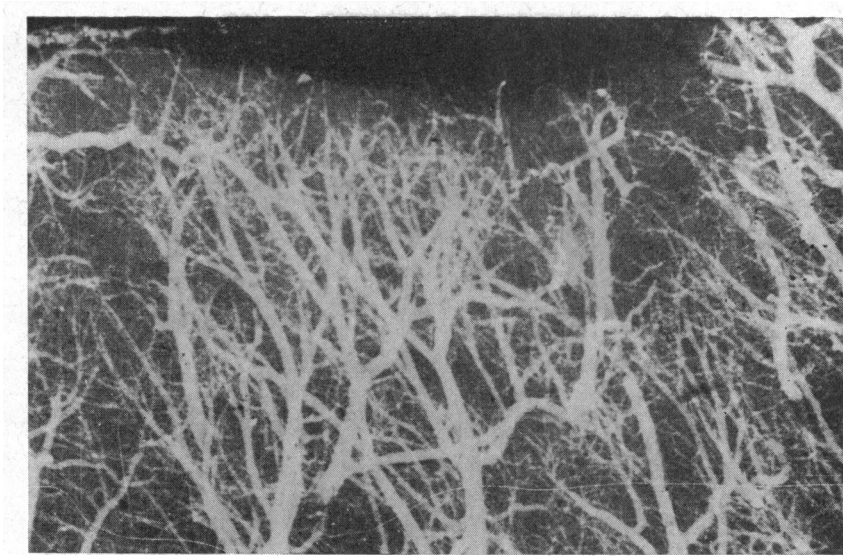
FIG. 2.—The "branching" type arteries terminate in the subendocardial zone of the left ventricle. (× 12.)

formed by branches from these straight type arteries

In the subepicardial zone the pattern was slightly different: before the main stems made their major divisions several branches were given off which ran in a more circumferential direction (Fig. 5). They, in turn, gave branches that coursed towards the pericardium, and communicated with vessels in the pericardial fat.

The final branching of small arteries as they formed arterioles showed two different patterns. Fig. 6 shows the first pattern, which is seen mainly in the subendocardial zone and illustrates the termination of the main arteries. This tree-like
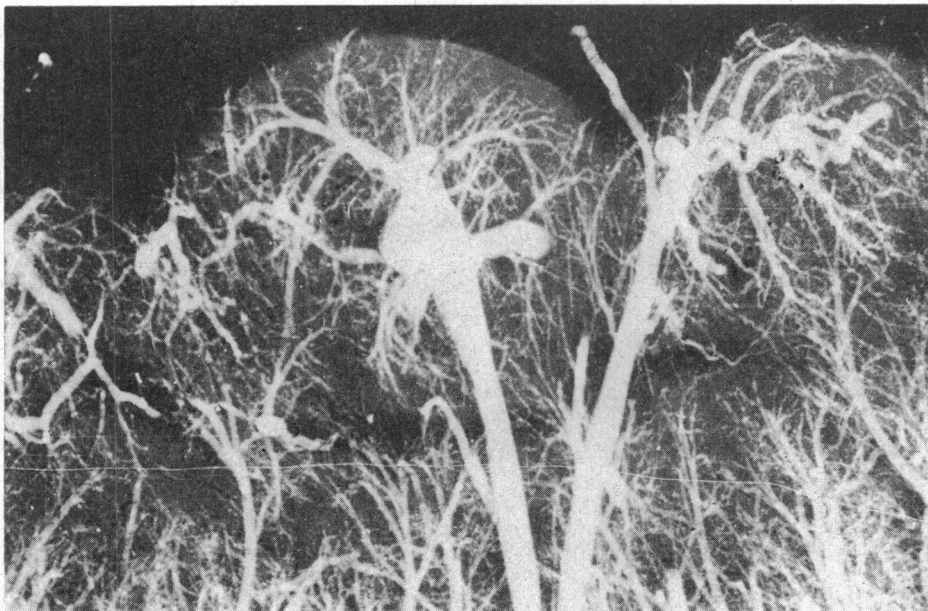

FIG. 3.—When "straight" type arteries supply the trabeculae carneae the "branching" type arteries supply the adjacent subendocardial zone. (× 13.)

Fig. 4.—"Straight" type arteries supply the anterior papillary muscle with similar, but smaller-sized, arteries supplying the trabeculae carneae.   (× 6.)
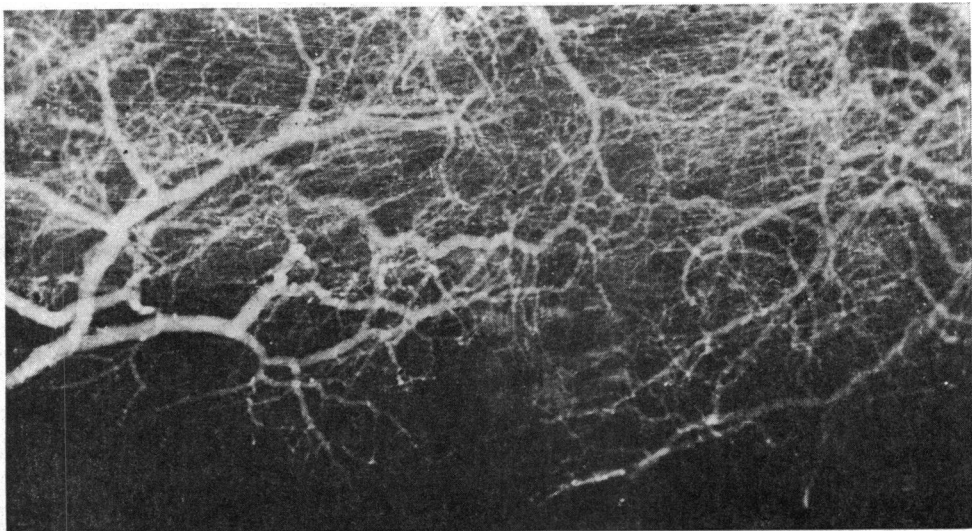

Fig. 5.—The subepicardial zone of the anterior wall of the left ventricle showing arteries coursing circumferentially and giving off branches towards the pericardium.   (× 14.)
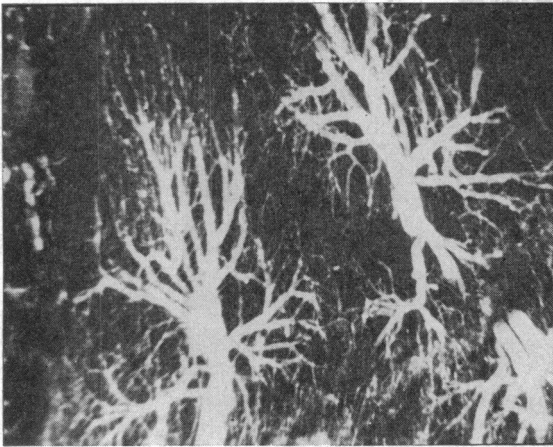
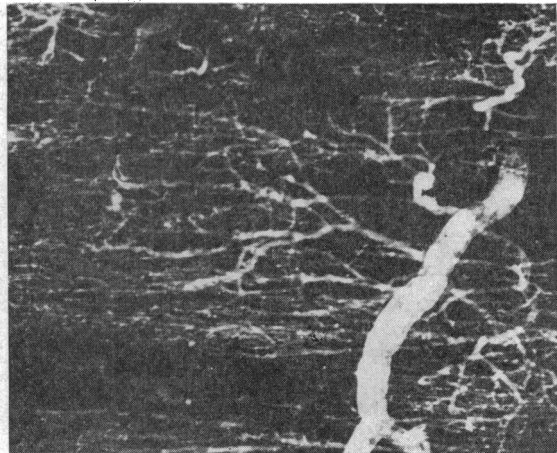FIG. 6.—The terminal brush-like branching of the small arteries is seen on the left of the photograph. (× 30.)

FIG. 7.—The final branches of small arteries in the middle of the myocardium. (× 24.)

branching follows the general direction of the line of the main artery, though arterioles cross myocardial fibres at varying angles before they divide into capillaries. A more widespread variant of this pattern is also seen in the mid-myocardial zone.

The second pattern, seen only in the middle of the myocardial wall, showed small arteries turning at right angles to the line of direction of the main artery and then dividing into only a few branches, which spread out sometimes over 180° to supply the muscle fibres in that immediate area (Fig. 7).

The capillaries in all areas ran parallel with the muscle with moderately frequent cross-connexions. Fig. 8 illustrates the capillaries of two muscle bundles running at an angle to each other. Higher

magnifications of these vessels and their cross-communications are seen in Fig. 9 and 10.

Papillary Muscles of Left Ventricle. The blood supply to the papillary muscles was mainly from "straight" type arteries. The anterior papillary muscle was usually supplied from branches of the left anterior descending artery, but occasionally from branches of the left circumflex artery. Branches from the posterior descending artery or the left circumflex artery supplied the posterior papillary muscle. This source of supply was usually similar to the adjacent area of myocardium of the posterior wall, but occasionally the adjacent myocardial wall was supplied by the right coronary artery, while the
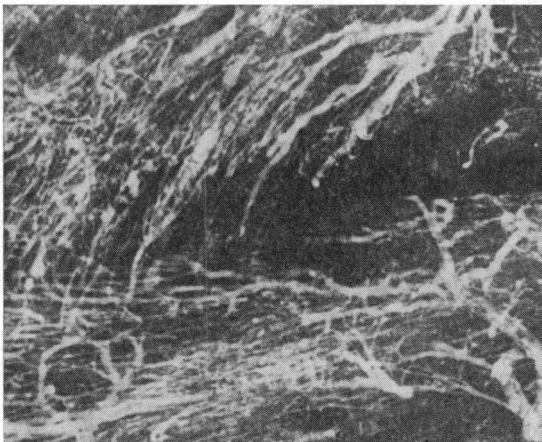

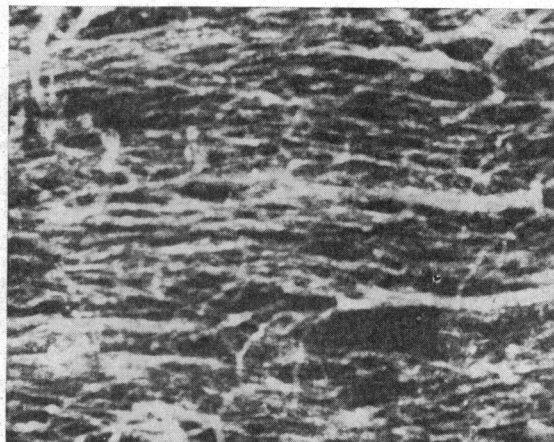FIG. 8.—Capillaries in the left ventricle running alongside muscle fibres. (× 24.)

FIG. 9.—A higher magnification of capillaries in the free left ventricular wall. (× 60.)

FIG. 10.—A high magnification of capillaries in the left ventricular wall seen in a 300 μ section to show the detail of a cross-communication.   (× 480.)
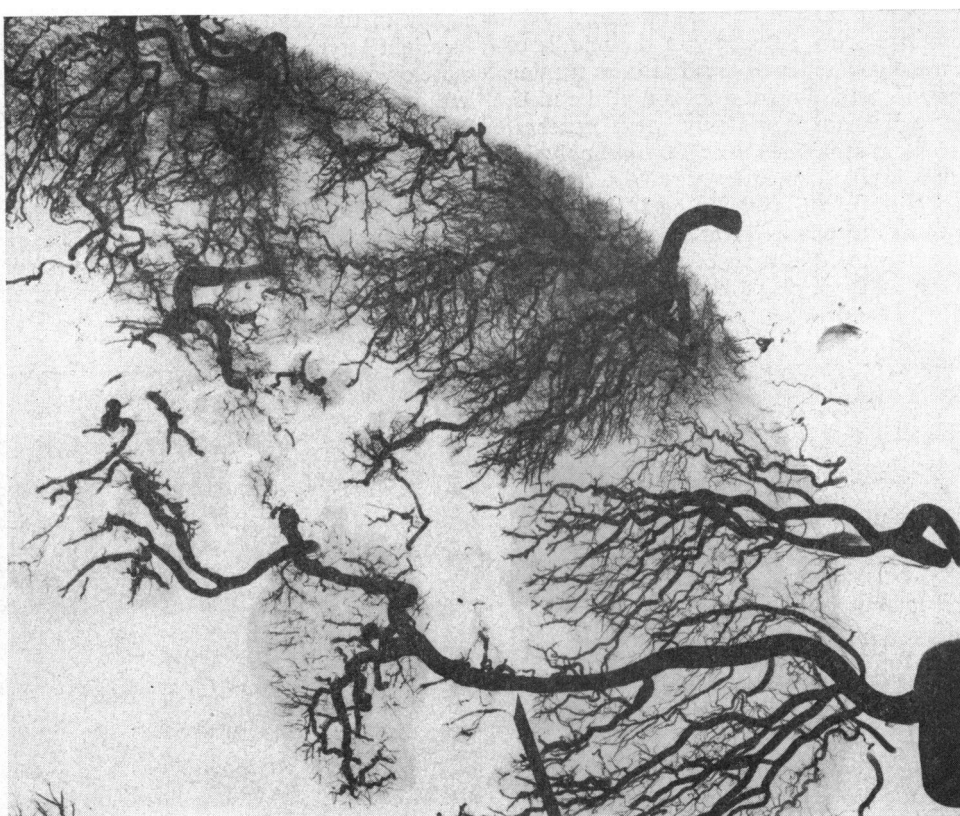

FIG. 11.—The posterior wall of the left ventricle of a heart with "Contrast" filling showing the posterior papillary muscle supplied by a branch of the left circumflex artery, while the adjacent myocardium is supplied by branches of the right coronary artery.   An area of fibrosis is present on the posterior wall.   (× 4.)

FIG. 12.—A microradiograph of the posterior half of the ventricles showing a "contrast" filling with the medium filling the capillaries in the right artery tree, but being confined to arteries of 40 μ or more in diameter in the left artery tree. (×1.8.)

papillary muscle was supplied by the left circumflex artery (Fig. 11).

The straight type arteries tended to pass through the middle of the papillary muscle giving off branches in all directions. The terminal vessels either coursed circumferentially around the perimeter or passed directly towards the edge of the papillary muscle, the variation being due to the direction of the muscle fibres.

Contrast Filling. In four hearts, Chromopaque of different viscosites, but at identical pressures, was injected down the left and right coronary arteries. An abrupt line of demarcation between the areas supplied by those two arteries was seen, in both the interventricular septum and the posterior wall of the left ventricle (Fig. 12). An enlargement showing minimal flow of medium across capillaries at the line of demarcation between the left and right coronary arteries, is shown in Fig. 13.

This appearance was obtained irrespective of whether the heart was from the "normal" or "abnormal" group, with the latter having obvious anastomotic vessels in the interventricular septum, and both when the arterioles of the left coronary tree were filled with medium and when this material was confined to arteries of 40 μ or more in diameter.

DISCUSSION

Microradiographs of hearts demonstrate that the major part of the left ventricular myocardium is supplied by "branching" type arteries regularly spaced around the free wall.

This type of artery has been mentioned by other workers such as Gross (1921), Campbell (1929), Mitchell and Schwartz (1965), and Fulton (1965), but it was not until 1966 that Estes *et al.* (1966b) attempted to define the width of myocardium that these arteries supplied. They described these vessels as being confined to the outer three-fourths to four-fifths of the myocardium. The observations in this current study do not agree with their description as the microradiographs show that the terminal branches of these arteries supply the subendocardial zone. This term, it will be recalled, is used to describe the innermost 2–3 mm. of the myocardial wall but does not include the trabeculae carneae.

The difference in the findings is probably due to the uniform filling of the finest terminal branches which is more easily accomplished by using Chromopaque as an injection medium than Micropaque used by Estes *et al.* (1966b). Secondly, these small vessels are more easily seen on high resolution plates than on the fine grain x-ray film used by these workers. In addition, filling of the most terminal branches can only be confirmed if the medium has been allowed to flow into the capillaries in the manner described in this study.

The importance of this finding is that these terminal branches of the "branching" arteries, rather than the subendocardial plexus, appear to provide the major blood supply to the subendocardial zone
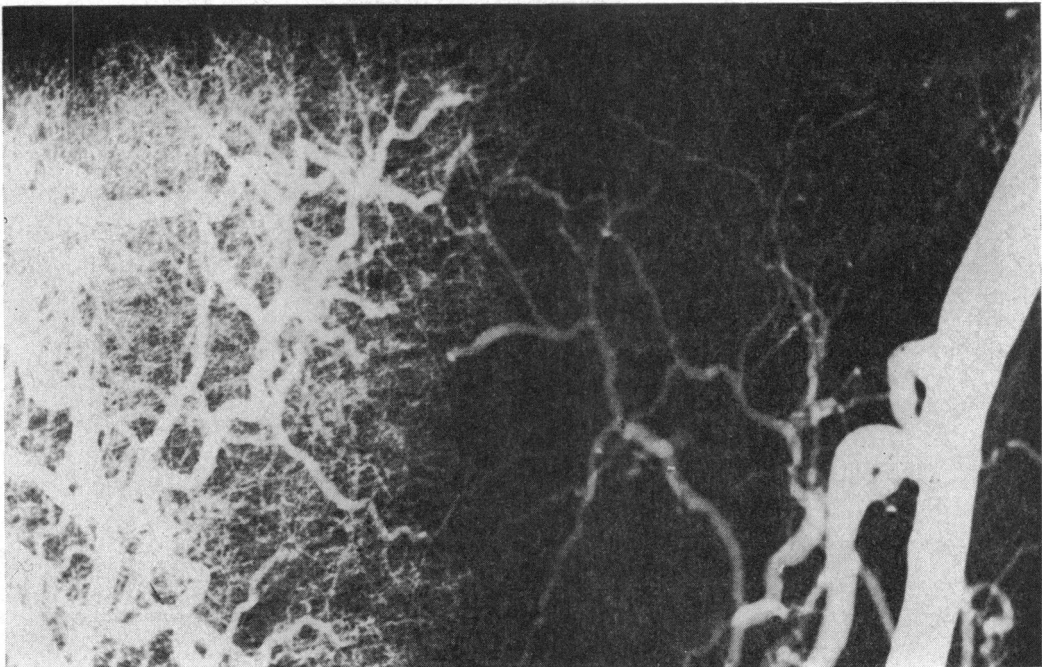
FIG. 13.—An enlargement of the posterior left ventricular wall from Fig. 12 showing that the flow of injection medium across capillaries at the line of demarcation between the areas supplied by the right and left coronary arteries is minimal. (× 16.)

in "normal" hearts.   Only when the subendocardial plexus is enlarged, as in hearts showing severe coronary artery disease, is the subendocardial plexus likely to be the provider of a major part of the blood supply to the subendocardial zone.

The microradiographs of the transverse slices showed that, in addition to the "branching" arteries, "straight" type arteries which coursed directly through the myocardium, giving off few branches, were present throughout the left ventricle.   These arteries have been described by Fulton (1965) and Estes et al. (1966a, b) as supplying the subendocardial anastomotic network and the papillary muscles.

This present study confirmed their findings, but, in addition, showed that the "straight" type arteries that supplied the papillary muscles were of larger calibre than similar type arteries seen in the remainder of the ventricular free walls.   The calibre of these "straight" type arteries remained fairly constant throughout the myocardium in contrast to the "branching" type arteries.   The occasional enlarged appearance of these vessels as they passed through the subendocardial zone was thought to be due to a lack of counter pressure during injection. This conclusion is in agreement with that proposed by Estes et al. (1966b).   Considering that the heart

develops from an arterial tube it is interesting that these "straight" type arteries to the papillary muscles are present in the myocardial walls of the ventricles.   Vasa vasorum of the aorta, or other main arteries, do not show this degree of penetration of the wall (Clarke, 1965).

It seems reasonable to suggest that these papillary muscles would not gain sufficient nutrition from the terminal branches of the "branching" type arteries and that a better blood supply is necessary than could be provided by them.

Whether the anatomical arrangements of these arteries result in the papillary muscles being less vulnerable to episodes of coronary artery ischaemia cannot unfortunately be resolved by post-mortem studies of this kind.   The arterial pattern within the papillary muscles, with the main artery being central and sending branches out towards the periphery, appears to be the most efficient way of ensuring a uniform distribution of blood.   The important role of the smaller "straight" type arteries is probably to supply blood to the trabeculae carneae.

In those hearts in which contrast filling was performed, it was found that the simultaneous injection of Chromopaque of different viscosities, but at identical pressures, down the left and right coronary arteries of four hearts produced an abrupt line of

demarcation between the areas supplied by these two arteries. The medium in the left coronary tree was confined either to the small arteries, or the arterioles, with blood remaining in the smaller vessels. The medium in the right coronary tree had flowed through the capillaries and in each case was beginning to flow into the venous system.

Although this finding has occurred in an *in vitro* experiment it seems reasonable to conclude that free flow across anastomotic vessels at capillary level probably does not occur, and it casts doubt on the idea that pre-capillary anastomotic vessels are of functional significance if equal pressures exist in the right and left coronary trees.

The findings in these four hearts are in disagreement with Gross's (1921) description that "there is no sharp line of demarcation between the supply of right and left coronary arteries, since not only do their branches overlap but also profuse and abundant anastomoses leave a wide borderline which is supplied by both vessels". This present study shows that there may be a sharp line of demarcation.

This current study has produced no evidence of the existence of a separate blood supply to the separate muscle bundles in the left ventricle, as suggested by Lowe (1939). The fact that capillaries run alongside muscle fibres throughout the whole of the myocardium does not support his suggestion. The arteries running circumferentially in the middle of the free myocardial wall as depicted in Lowe's (1939) drawings have not been seen in the free wall of the left ventricle in normal hearts. Only when extensive generalized fibrosis of the myocardium is present, with loss of normal arterial pattern, are arteries seen coursing in a circumferential direction in this area of the wall.

Before this study there was no previous description in the English literature of the pattern of the blood supply of the outermost layer of the myocardium with arteries running more circumferentially. This arrangement is probably purely anatomical and provides the area with an adequate blood supply. Furthermore, it permits the course taken by anastomotic vessels passing out into the epicardial fat to be straightforward. As scarring of this area is uncommon unless full thickness infarcts are present, it is concluded that its blood supply is generally satisfactory.

Small Arteries and Arterioles. The microradiographs of the hearts showed that there were two basic types of pattern of the smallest arteries and arterioles as they divided into capillaries within the myocardial wall. The direction of the tree-like branching in the subendocardial zone continued in the general line of the main artery. The area of

myocardium supplied by these vessels was fairly small. This was in contrast to the other pattern in the middle of the myocardial wall, where the arterial branches turned more at an angle to the main artery and then divided to supply a much wider area of myocardium than was supplied by the terminal branch in the subendocardial zone.

The reason for these patterns is probably the fact that the type of branching seen in the middle of the wall supplies a wide area of myocardium without the need for numerous branches to be given off by the main artery. By the time the subendocardial zone is reached, the main artery has subdivided so many times that each terminal branch needs to supply only a small area.

On the other hand, it may be an anatomical arrangement so that the blood supply to the subendocardial area is more straightforward and more abundant, in order to ensure that the blood supply is sufficient, despite the increased pressure in this area (Johnson and Di Palma, 1939) and its remoteness from the blood supply (Friedberg and Horn, 1939).

Capillaries. The examination of 14 adult hearts in this current study in which injection of capillaries was performed has confirmed the findings of Gross (1921) and Wearn (1928) that capillaries follow the direction of the muscle fibres, with a moderate number of cross-communications being present. All the hearts studied had one capillary per muscle fibre. The manner in which capillaries run parallel to muscle fibres is best seen in the inner quarter of the left ventricular myocardium where muscle bundles from trabeculae carneae and papillary muscles blend together. In some areas where the muscle bundles have been cut across the capillaries are seen end on. The density of capillaries of the left and right ventricles, including the interventricular septum, as seen in the microradiographs of the transverse myocardial slices, appeared similar. These findings were again not in support of the suggestion of Gross (1921) that the vascularity of the right ventricle decreased with age.

SUMMARY

The normal arterial pattern of the myocardium of the left ventricle seen in 52 human hearts was studied *post mortem* by injection of a radiopaque medium, Chromopaque, and the taking of microradiographs of transverse ventricular myocardial slices on Kodak high resolution plates.

"Branching" type arteries supplied the whole of myocardium wall, including the subendocardial zone, while "straight" type arteries mainly supplied the papillary muscle and trabeculae carneae. The

patterns of these two types of arteries, of the division of small arteries into arterioles and of capillaries, are illustrated. The appearances seen on "contrast" injections of Chromopaque of different viscosities, but at identical pressures, down the left and right coronary tree are also described.

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